NAVORD REPORT 2752

MEASUREMENT OF BOUNDARY-LAYER TRANSITION ON A STANDARD MODEL TO DETERMINE THE RELATIVE DISTURBANCE LEVEL IN TWO SUPERSONIC WIND TUNNELS

19 FEBRUARY 1953

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

UNCLASSIFIED
NAVORD Report 2752

Aeroballistic Research Report 170

MEASUREMENT OF BOUNDARY-LAYER TRANSITION ON A STANDARD MODEL TO DETERMINE THE RELATIVE DISTURBANCE LEVEL IN TWO SUPERSONIC WIND TUNNELS

Prepared by:

A. H. Lange and L. P. Gieseler

ABSTRACT: Boundary-layer transition on a slender cone was observed at various Mach numbers between 1.9 and 4.2 in the NOL Supersonic Wind Tunnels No. 2 and 3. The Reynolds number of transition was found to be different in the two tunnels. A decrease of Reynolds number of transition with increasing Mach number was observed in the range of Mach numbers investigated. For a fixed Mach number, the transition Reynolds number could be lowered by introducing upstream disturbances in the wind-tunnel supply section. From the results of this investigation the conclusion is drawn that the slender cone is a suitably sensitive standard model to indicate differences in the free stream disturbance level of supersonic wind-tunnel flows. The tests also show that flow disturbances in the subsonic part of a tunnel are propagated through the Laval nozzle in a way to affect the transition in the boundary layer of a model placed in the supersonic stream.

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

NAVORD Report 2752 19 February 1953

Data on the boundary-layer transition on a standard model are presented and conclusions are drawn regarding the relative disturbance level in two NOL supersonic tunnels. The investigation is exploratory in character, but is of practical importance for the correlation of wind-tunnel data taken in different facilities, and for the correlation between wind tunnel and flight.

The work was initiated in November, 1951 by the authors and Mr. J. L. Potter who was at that time with NOL. Negotiations concerning the use of the model at other wind-tunnel facilities in the country are planned. The authors wish to thank Mr. R. K. Squires who participated in the tests, and Mr. R. T. Schroth who designed the model.

EDWARD L. WOODYARD
Captain, USN
Commander

H. H. KURZWEG, Chief
Aeroballistic Research Department
By direction

CONTENTS

ILLUSTRATIONS

MEASUREMENT OF BOUNDARY-LAYER TRANSITION ON A STANDARD MODEL TO DETERMINE THE RELATIVE DISTURBANCE LEVEL IN TWO SUPERSONIC WIND TUNNELS

I. INTRODUCTION

1. It is well known that the turbulence level of the airflow in a wind tunnel affects boundary-layer transition (reference 1). It is important, therefore, to know the free stream turbulence level of a wind tunnel in order to make correct interpretation of wind-tunnel data.

2. While the technique of directly measuring free stream turbulence in subsonic flows is well mastered, it is in its first stages in supersonic flows and direct measurements are very difficult (reference 2). A standard model technique, comparable in scope to the standard sphere technique which had been common in subsonic wind tunnels before the development of hot wire anemometry (references 1 and 3), was therefore used to deduce information on the free stream disturbance level of the airflow in two of the NOL supersonic tunnels.

3. A 5° total apex angle cone, about 50 cm long and 4.5 cm in diameter at the base, served as the standard model. Transition in the boundary layer of the cone was determined by two methods, the luminescent lacquer technique and spark-schlieren photography, the latter method being used in the majority of the tests. Details of the model and of the two methods will be given in sections II and III.

4. The cone was chosen as a standard model for the following reasons:

(a) The head shock wave can be made weak by choosing small cone angles. Its influence on the boundary-layer transition is thereby minimized.

(b) The pressure is constant along the cone surface in supersonic flow. The influence of a pressure gradient on the boundary-layer transition is therefore eliminated.

(c) The boundary-layer transition can be determined optically; the hazards of probe interference are thereby eliminated. On a two-dimensional model this would not be feasible because of transverse contamination.

(d) The laminar boundary layer in supersonic conical flow has been treated theoretically, and experimental transition data are of interest in the analysis.

5. The tests supplied information on:

(a) The transition Reynolds numbers in the Aeroballistics Tunnels No. 2 and the Aerophysics Tunnel No. 3 under approximately equal tunnel supply conditions at Mach numbers 3.25 and 4.25,

(b) The Reynolds numbers of transition as a function of Mach number in Tunnel No. 2. The data were taken at Mach numbers 1.87, 2.15, 2.87, 3.25, and 4.25,

(c) The effect of disturbances introduced by screens in the subsonic portion of the wind tunnel on the transition Reynolds numbers in Tunnel No. 3 at Mach numbers 3.25 and 4.25.

6. Incidental information was obtained on:

(d) The effect of the two methods used for detecting transition,

(e) The effect of model imperfection, and

(f) The effect of a boundary-layer trip on transition.

II. TEST EQUIPMENT

(a) Wind Tunnels

7. The NOL Aeroballistics Wind Tunnel No. 2 has a 40 x 40 cm open test section. The supply air is taken from the atmosphere through a drier and straightener. The operation is intermittent and blows up to 1 minute duration can be made.

8. The NOL Aerophysics Wind Tunnel No. 3 has a 18 x 18 cm closed test section. The supply air is also taken from the atmosphere through a drier but no straightener is in the supply duct. The operation of the tunnel is continuous.

9. Both tunnels are described in more detail in reference 4.

(b) Model

10. Details of the model are shown in Figure 1. The first tests were made with a chromium plated brass cone which we will call "first version". Its surface had been ground before plating in a number of lengthwise sections while the model

was supported near the tip of the cone. The blending of these sectional grinds was not smooth. Figure 2 shows the deviations of the surface of this model from an ideal cone surface.

11. When the "second version" was manufactured the model was held at the cylindrical part only and the entire conical surface was machined in one continuous travel of the grinding wheel. This produced a true conical surface with a .03 mm radius point. The second version was also made of brass and no plating was applied.

12. The surface roughness of the second version was recorded with a Brush Surface Analyzer, Type PA 2. The record showed an average roughness of 0.25 microns, with occasional roughness elements as high as 1.0 microns. (One micron = 39.4 microinches). This value is given here that the roughness may be compared with that of models measured with the same type of instrument at other laboratories. It is felt that the quantitative indication of the instrument is a relative measure of the roughness only, because the radius of the tip of the stylus that feels along the surface is considerably larger than the indicated roughness.

13 The authors estimate that the roughness may actually be larger than indicated. However, even then the surface roughness may not be affecting transition at Mach numbers above the order of 2.5 as can be seen from the following considerations. Figure 3 is a plot of the mean free path of the molecules in the air stream vs. Mach number for a tunnel with atmospheric supply. Two curves are shown. One curve gives the mean free path near the surface of the model, assuming a temperature recovery factor $r = 0.9$. The other curve gives the mean free path in the free stream. The curves were determined from the equations

$$L = 9.29\ 10^{-6}\ \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{1}{\gamma-1}}\ [\text{cm}]\ \text{(free stream)},$$

and

$$L_W = L\ \left(1 + r\ \frac{\gamma-1}{2} M^2\right) \qquad [\text{cm}]\ \text{(wall)}$$

which were derived from elementary kinetic theory (reference 5) on the assumption of a supply pressure of 760 mm Hg and a supply temperature of 293°K. The measured peak surface roughness of 1 micron is shown to scale as a horizontal line in Figure 3. It is evident that a roughness which is even two to three times larger, is of the order of the mean free path for a Mach number of 2.5 and considerably smaller than the mean free path for all higher Mach numbers.

(c) Screens

14. The screens used in some tests in Tunnel No. 3 were placed in the 18 cm x 23.5 cm cross-section of the supply duct about 5 cm upstream from the nozzle blocks, that is, close to the beginning of the two-dimensional contraction leading to the nozzle throat (see Figure 4). The screens were made from commercial square wire mesh. The "coarse screen" had wires 0.097 cm in diameter, spaced 0.2 cm between centerlines, and the "fine screen" had wires 0.028 cm in diameter, spaced 0.16 cm between centerlines.

(d) Straightener in Tunnel No. 2.

15. The straightener in Tunnel No. 2 was located 200 cm upstream from the beginning of the supersonic nozzle in a 120 cm x 130 cm cross-section of the supply duct. It consisted of 0.05 cm thick sheet metal forming square tubes 4.6 cm on a side and 35 cm long (see Figure 4).

III. TEST PROCEDURE AND EVALUATION

16. Luminescent lacquer technique: This technique is described in reference 6*. In our case the model was spun rapidly around its axis of symmetry in a jig while it was sprayed with the lacquer in order to secure

---

* A lacquer which is a mixture of a carrier, a solvent, and luminescent particles is used. A coat of this lacquer viewed in ultra violet light looks light when dry and dark when wet. The higher rate of evaporation in the turbulent boundary layer of a model coated with the lacquer causes the lacquer to dry where the boundary layer of the model is turbulent long before it dries where the boundary layer is laminar, and those regimes are therefore clearly visible as light (turbulent) and dark (laminar) areas on the model.

uniform application. The model was then put into the tunnel and subjected to supersonic flow for a length of time just sufficient to dry the lacquer in contact with the turbulent boundary layer. Thereafter the model was taken from the tunnel and photographed from four sides in ultra violet light. Figure 5 shows some typical photographs. The method was abandoned later during the tests because of the unknown effect of the coating on the transition itself and the hazard that coatings of different thickness might influence the results by giving different Reynolds numbers of transition for equal ambient conditions.

17. Spark-schlieren photographs: Schlieren photographs of about 1 microsecond exposure time were taken of the model in the tunnel. The location of boundary-layer transition was then determined on the photographs as the point where the smooth outline of the laminar boundary layer breaks up into a turbulent structure. This point was considered as corresponding to the beginning of transition.

18. A typical test with the latter technique proceeded as follows: Using the continuous light source of the schlieren apparatus, the knife edge was put in a position nearly parallel to the model contour and adjusted while the wind tunnel was blowing until maximum contrast appeared at the boundary layer. Another blow was then made during which six flash photographs were taken in succession at about 3 second intervals. This procedure was then repeated after the knife edge had been rotated 180°. Since the boundary layer was visible on the upper and on the lower side of the model contour, the above procedure yielded in two blows 12 pictures with 24 values of the location of transition. A typical schlieren photograph is reproduced in Figure 6. Pictures taken with vertical knife edge adjustment and with the shadowgraph method were inferior.

19. The distance of the transition point from the tip of the cone, l, is used to compute the Reynolds number of transition,

$$Re = \frac{u \cdot l}{\nu}$$

where, u, is the velocity and, ν, is the kinematic viscosity of the undisturbed flow determined from nozzle calibrations.

20. Whenever a large number of test points was obtained for the same test condition, the results were treated in the following manner: The arithmetic mean, the largest value, and the smallest value were reported. In addition, the spread, s, of one half of the observations about a mean value was determined. This spread was determined from the equation

$$s = 0.8453 \frac{\sum |v|}{\sqrt{n\,(n-1)}}$$

given, for instance, in reference 7. The equation is an approximate formula for the probable error of a single observation. The interval determined in this way is in our case not a measure of error but rather a measure of the amount that the Reynolds number of transition fluctuates with time. It is indicated as a thick vertical bar in the graphs, Figures 7, 8 and 10.

IV. RESULTS

21. Figure 7 shows a comparison of the Reynolds number of transition observed in tunnels No. 2 and 3. The ordinate is the Reynolds number of transition. The mean value, the total spread, and the spread of one-half of the values are shown for both tunnels. The number of values from which each plot was reduced is noted. The figure shows that the Reynolds number of transition is consistently about one million higher in tunnel No. 3 than in tunnel No. 2. The imperfect first version of the model gives the same qualitative behavior in both tunnels as the improved second version. However, the level of transition Reynolds numbers is reduced by approximately 1/2 million. The results at Mach number 4.25 are less conclusive than those at Mach number 3.25 because an important part of the model was invisible due to the presence of a steel rib in the tunnel sidewall. The value of the transition Reynolds number could only be bracketed between 1.6 and 2.0×10^6 for the boundary layer on the lower side of the cone. The upper side appeared laminar throughout.

22. It may be concluded from the higher Reynolds number of transition in Tunnel No. 3 that the disturbance level is lower there than in Tunnel No. 2 at Mach numbers 3.25 and 4.25. The lower turbulence level in Tunnel No. 3 may be caused by the absence of a straightener and the higher contraction ratio of this tunnel and the subsequent lower turbulence level in the intake.

23. The variation of Reynolds number of transition with Mach number in Tunnel No. 2 is shown in Figure 8. A decrease of Reynolds number of transition with increasing Mach number was observed.

24. In Figure 9 the results are compared with transition data obtained on other bodies of revolution. The curves of references 8 and 9 represent transition Reynolds numbers observed in the same tunnel. In reference 8 boundary-layer transition was observed in the same fashion as in the present report on a "Hollow Cylinder"; i.e., a tube with a sharp leading edge. Supersonic flow enters the tube and a weak shock is formed at the leading edge. The curve of reference 9 represents the Reynolds number at which the skin-friction drag of a cone-cylinder body of variable length increases suddenly. The curve denoted by "ogives NACA", reference 10, was obtained in a continuous wind tunnel on a slender ogive body with an extremely smooth surface. This curve too represents Reynolds numbers at which the sudden increase in skin-friction drag occurs (minimum of boundary-layer displacement thickness). Some single experimental points, found in the literature, references 11, 12, are also shown. The points denoted by triangles are the only non-wind-tunnel data of this graph. They were obtained from shadowgraphs of cone-cylinder bodies that were fired in the range of the Ballistics Research Laboratory, Aberdeen. Transition occurred in the conical forepart of the missiles. The data were taken from reference 13.

25. The NOL wind-tunnel data ar in good agreement with each other. All show decreasing Reynolds numbers of transition with increasing Mach numbers. The same trend is exhibited by the NACA data at the lower Mach numbers. Decrease of the Reynolds numbers of transition with increase in Mach number is to be expected from boundary-layer stability theory, reference 14, in the wind tunnel where the ratio of wall temperature to equilibrium temperature is unity or, in an intermittent tunnel, slightly above unity ($T_W/T_E = 1$). To illustrate this the theoretical curves of minimum Reynolds number at which transition could occur, i.e., the Reynolds numbers of neutral stability of two-dimensional disturbances in the laminar boundary layer, are also shown for $T_W/T_E = 1$ and $T_W/T_E = 2$ in Figure 9. It is seen that the experimentally determined trend does not deviate decidedly from

the theoretical prediction. The large deviation in absolute value of 3 to 4 orders of magnitude must await further clarification. Although some deviation is to be expected, the combined effects of free stream turbulence and noise, surface roughness of the body, heat-transfer conditions in the boundary layer, and pressure gradient introduced by the model or inherent in the flow, can hardly explain the magnitude of the obse ved deviation.

26. An opposite trend, increasing Reynolds numbers of transition in the wind tunnel with increasing Mach numbers, is stated in reference 13. In the light of the evidence presented here and in the reference, such a trend appears doubtful. It is seen that even the range data, which should show th's opposite trend due to the different heat-transfer situation, do not point it out clearly. However, the relative roughness of the constant absolute-roughness missiles increases with Mach number, which may account for this behavior.

27. Figure 10 shows the effect of screens placed in the subsonic supply duct of Tunnel No. 3 at M = 3.25. The coarse and the fine screen reduced the Reynolds number of transition by 1.2 and 1.1 million with respect to the case of no screen.

28. A comparison of the two methods used to determine transition showed that the methods agreed fairly well. The lacquer technique gave lower Reynolds numbers of transition than the spark-schlieren photographs but the averages never differed by more than 0.2 million. (All results shown in the graphs of this report are derived from spark-schlieren photographs).

29. The effect of model imperfections can be seen in the left half of Figure 7 where results obtained at M = 3.25 with the first and second versions of the model are shown. With the second version Reynolds numbers about 0.5 million larger are observed in both tunnels.

30. A small rubber O-ring put on the cone as a boundary-layer trip appeared to be ineffective at M = 1.86 and at M = 4.25 but lowered the Reynolds number of transition in the middle of the Mach number range M = 2.83 and 3.25. However, the schlieren pictures were difficult to read and interpret, and results are therefore not presented in detail.

31. The surface temperature of the cone was not measured during the tests. It is slightly above recovery temperature in the intermittent Tunnel No. 2 and it is equal to recovery

temperature in the continuously operating Tunnel No. 3. In order to minimize the effect of a model temperature higher than equilibrium temperature, repeated blows were made in Tunnel No. 2 before the transition was determined. From earlier tests during which temperatures were measured on a cone-cylinder, it can be concluded that the transition Reynolds number is altered due to the remaining temperature deviation by less than 0.2 million.

V. CONCLUSIONS

32. The location of the boundary-layer transition on a slender cone has been shown to be influenced by:

(a) The flow conditions of a particular tunnel.

(b) The free stream Mach number.

(c) Turbulent disturbances produced by screens in the subsonic portion of the tunnel.

33. As a result of the investigation, it can be concluded that the location of the transition is a measure of the disturbance level in the wind tunnel, and that the slender cone is a suitable model to indicate differences in disturbance level. Although we cannot completely rule out the influence of model temperature, it appears that Tunnel No. 2 has a higher disturbance level than Tunnel No. 3 at the same Mach number. Disturbances introduced in the subsonic portion of the tunnel appear in measurable magnitude in the supersonic flow. A decreasing Reynolds number of transition with increasing Mach number was observed. This, however, may be a specific feature of the type of wind tunnel in which a large change of free stream conditions accompanies a change in Mach number.

VI. NOTATION

l	-	Distance from tip of cone to transition region.
u	-	Free stream velocity.
ν	-	Free stream kinematic viscosity.
Re	-	Reynolds number of transition based on free stream properties.
M	-	Free stream Mach number.
T_o	-	Supply temperature.
T	-	Free stream temperature.
T_w	-	Temperature on surface of model.
T_E	-	$= r T_o - (r-1)T$, Equilibrium temperature, temperature associated with zero heat transfer.
r	-	$= (T_E - T)/(T_o - T)$, temperature recovery factor.
L	-	Mean free path of air molecules in the free stream.
L_w	-	Mean free path of air molecules near the wall.
n	-	Number of observations.
s	-	Probable error of a single observation.
v	-	Deviation of a measurement from the mean.
γ	-	Specific heat ratio.

VII. REFERENCES

1. Prandtl, L., Der Luftwiderstand von Kugeln, Nachr. d.k. Gesellsch. f. Wiss., Goettingen, Math. Phys. Klasse (1914), p. 177.

2. Kovasznay, L. S. G., Turbulence in Supersonic Flow, Institute of the Aeronautical Sciences, 21st Annual Meeting, New York, 27 January 1953.

3. Dryden, H. L. and Kuethe, A. M., Effect of Turbulence in Wind-tunnel Measurements, NACA TR 342, 1929.

4. Lightfoot, J. R., The Naval Ordnance Laboratory Aeroballistic Facility, Naval Ordnance Laboratory Report 1079, 15 August 1950.

5. Kennard, E. H., Kinetic Theory of Gases, First Edition, McGraw-Hill, New York, (1938) pp. 97-115.

6 Stalder, J. R. and Slack, E. G., The Use of a Luminescent Lacquer for the Visual Indication of Boundary-Layer Transition, NACA TN 2263, January, 1951

7 Mellor, J. W., Higher Mathematics for Students of Chemistry and Physics, Dover, New York, (1946), p. 524.

8 Lee, R. E., Measurements of Pressure Distribution and Boundary-Layer Transition on a Hollow Cylinder Model. NAVORD Report 2823, Naval Ordnance Laboratory, White Oak, Maryland, March 1953.

9. Potter, J. L., New Experimental Investigations of Friction-Drag and Boundary-Layer Transition on Bodies of Revolution at Supersonic Speeds, NAVORD Report 2371, Naval Ordnance Laboratory, White Oak, Maryland, April 1952.

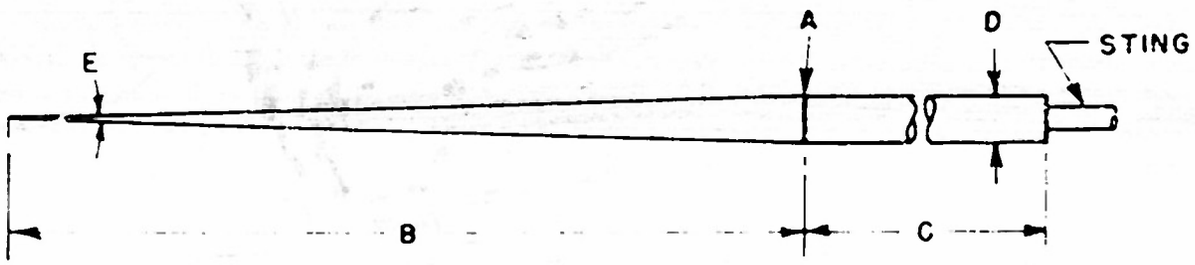
10. Love, E. S., Coletti, D. E., and Bromm, A. F., National Advisory Committee for Aeronautics, Unpublished data, 9 x 9 inch Tunnel.

11. National Advisory Committee for Aeronautics, Unpublished data, 9 x 9 inch Tunnel.

12. Chapman, D. R., An Analysis of Base Pressure at Supersonic Velocities and Comparison with Experiment. NACA Report 1051. Washington, D. C., 1951.

13 Gazley, C Jr , Boundary-Layer Stability and Transition in Subsonic and Supersonic Flow, Journal of the Aeronautical Sciences, 20, 1, 19 January 1953.

14 Van Driest, E. R., Calculation of the Stability of the Laminar Boundary Layer in a Compressible Fluid on a Flat Plate with Heat Transfer. Journal of the Aeronautical Sciences, 19, 12, 801, December 1952.



MACH NO.	APPROX. Re AT "A"
1.87	6.93×10^6
2.15	8.13
2.87	4.13
3.25	3.58
4.25	2.07

	VERSION	
	1 ST.	2 ND.
B	50.8CM.	51.7CM.
C	25.4	23.7
D	4.45	4.41
E	5°	4°-50'

FIG. 1 CONE MODEL

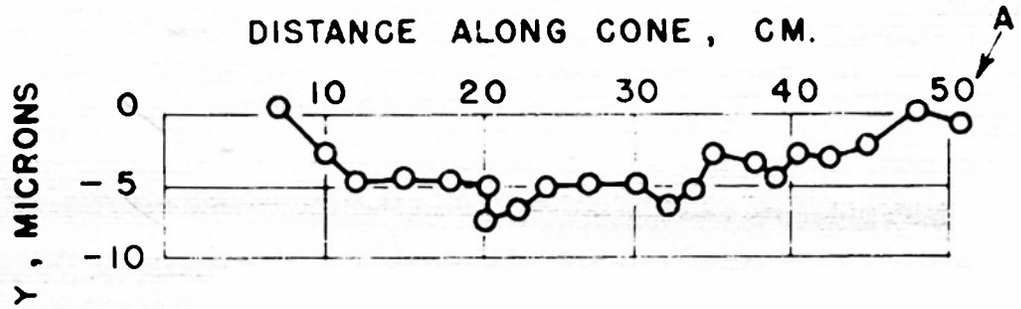


FIG. 2 PROFILE OF FIRST VERSION OF CONE

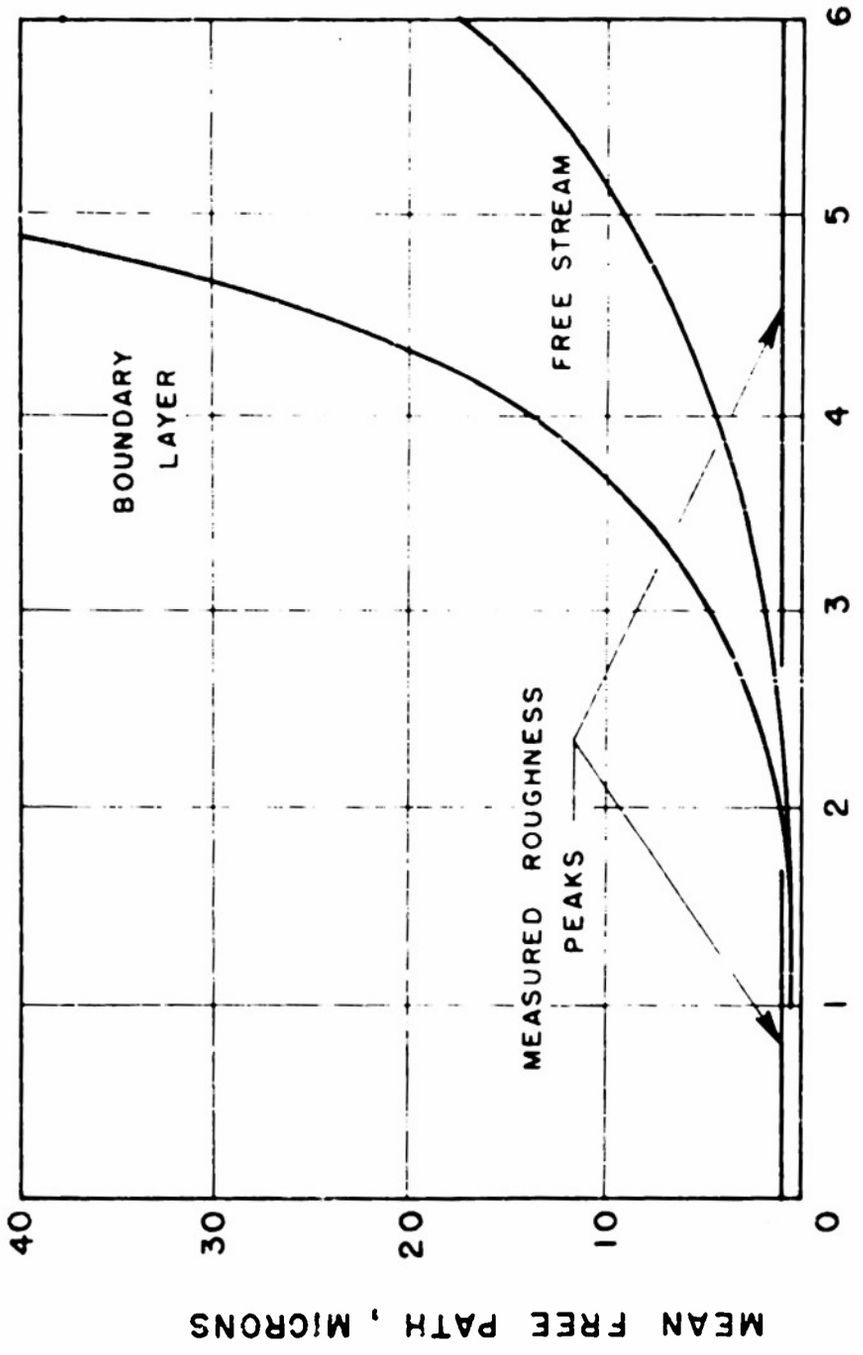


FIG. 3 MEAN FREE PATH VS. MACH NUMBER IN WIND TUNNEL WITH ATMOSPHERIC SUPPLY

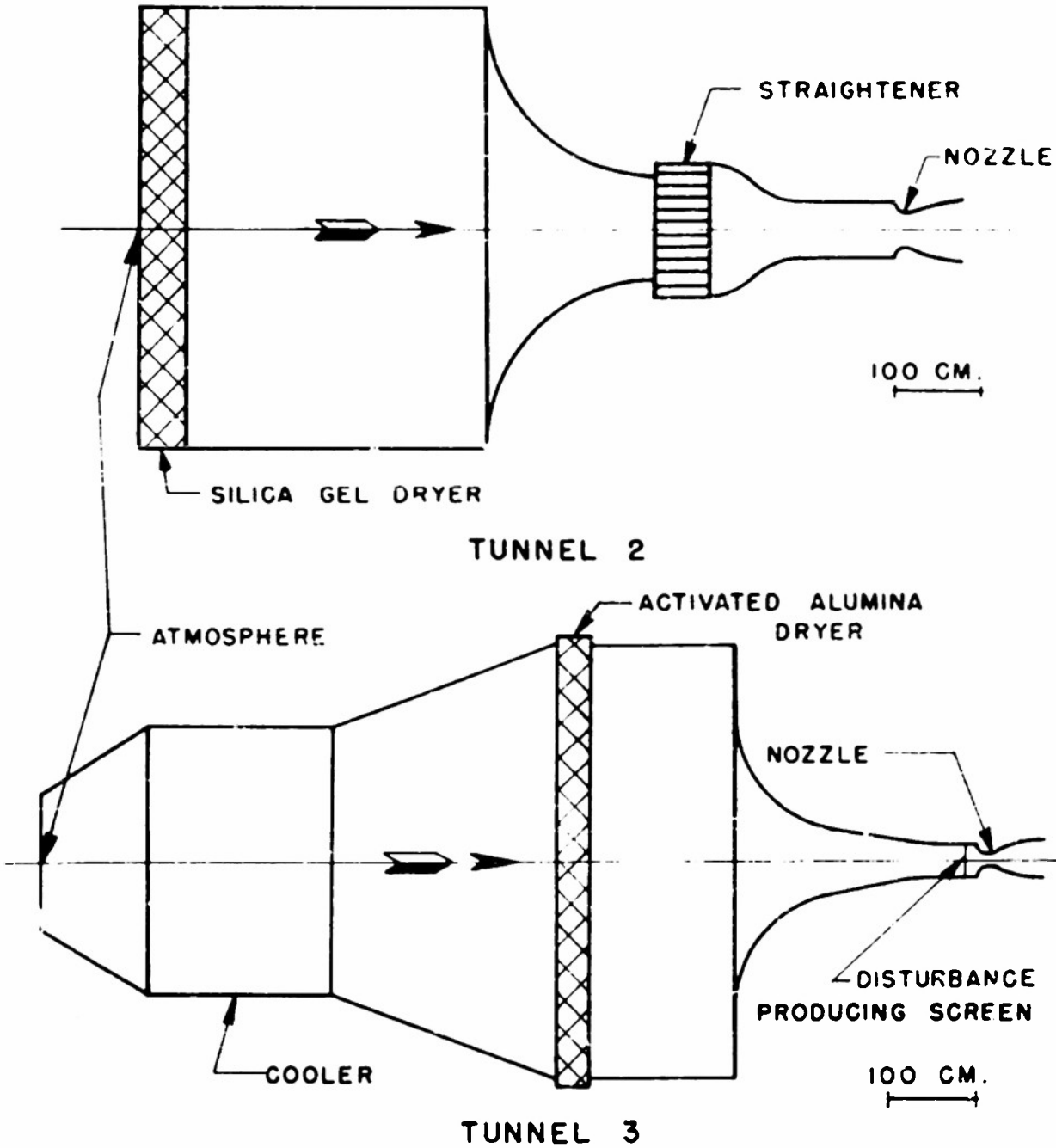


FIG. 4 INTAKE SECTION OF TUNNEL 2 AND 3

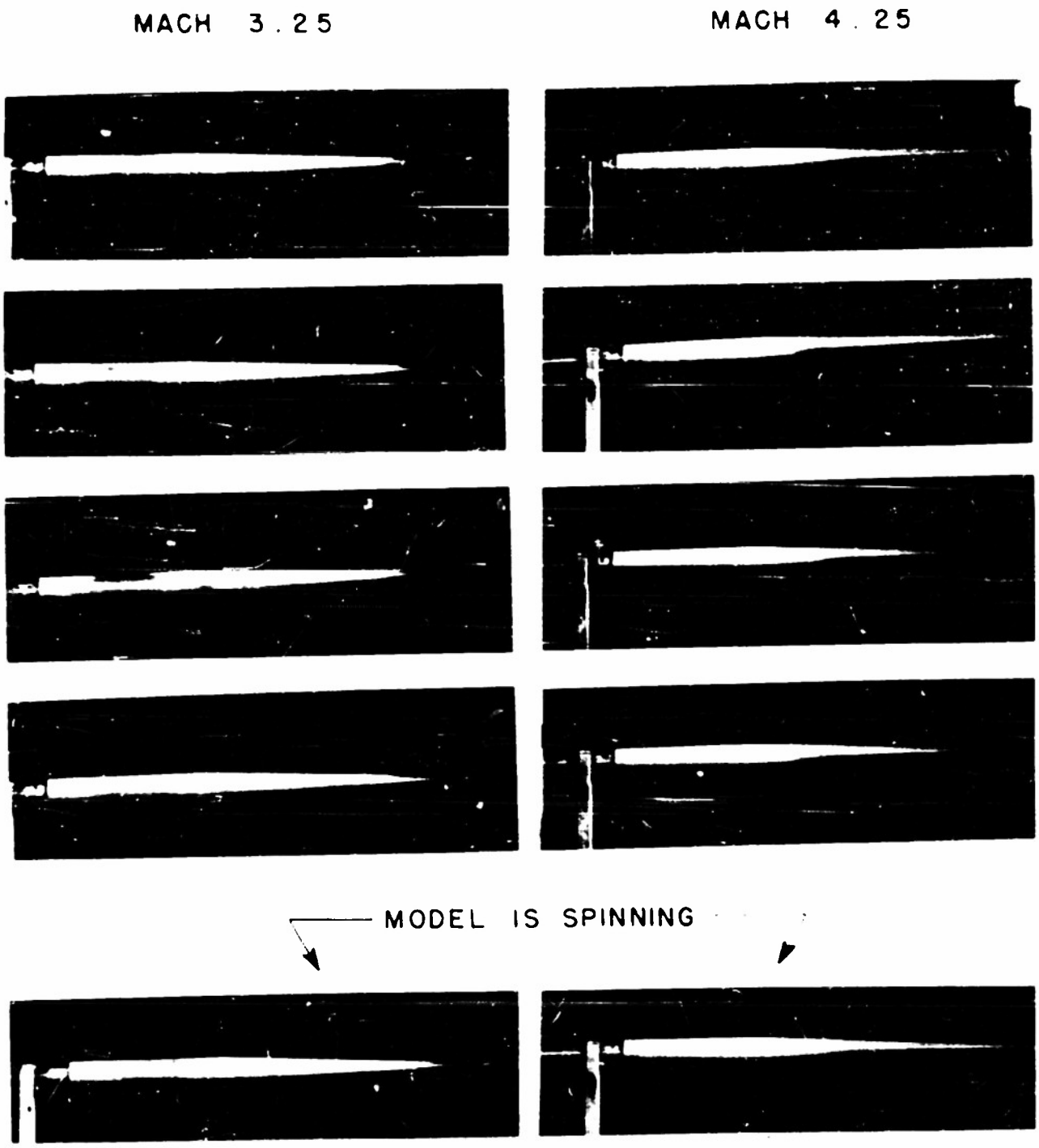
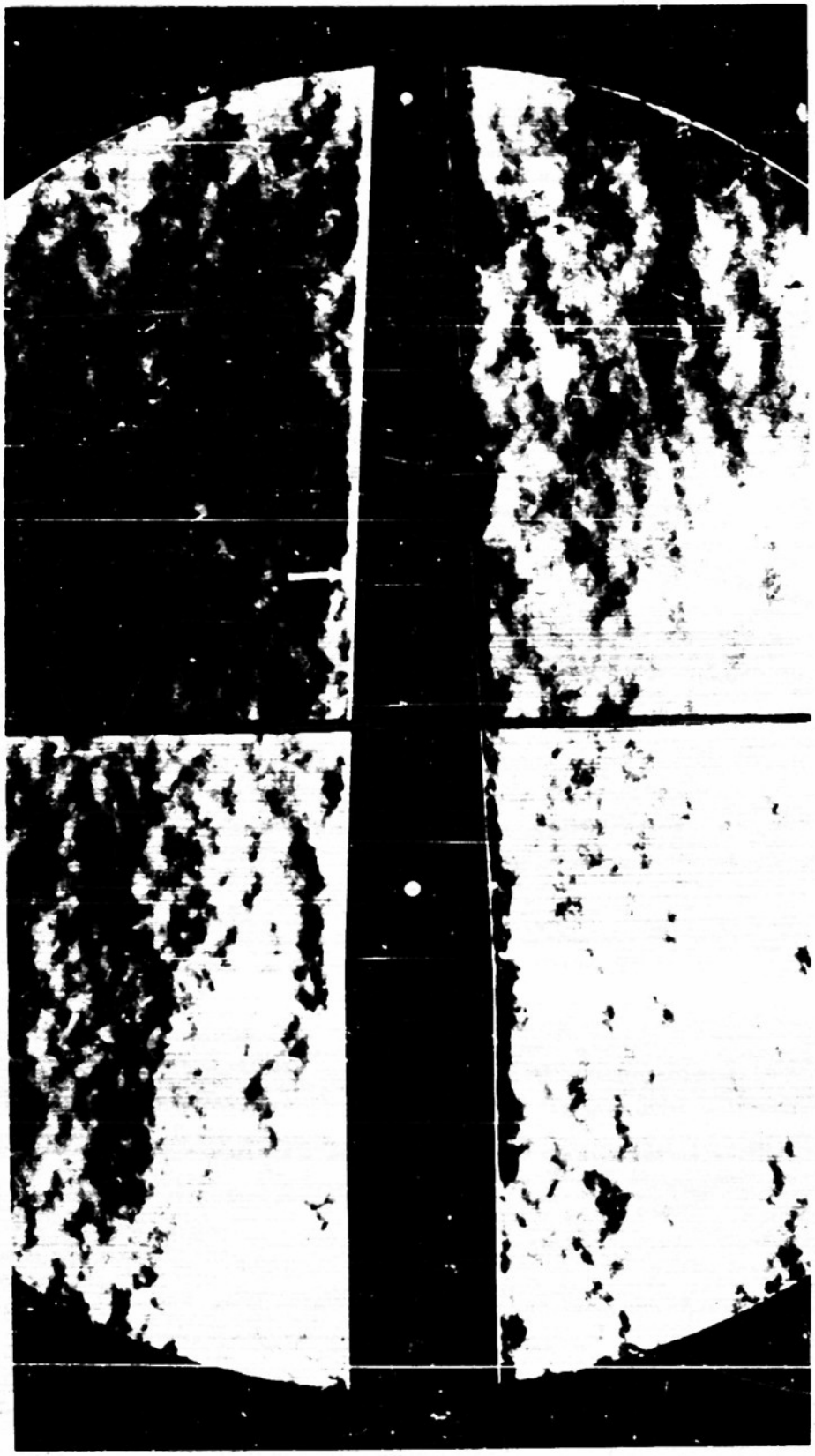


FIG. 5 REGIONS OF LAMINAR (DARK) AND TURBULENT (LIGHT) BOUNDARY LAYER FLOW ON STANDARD CONE MODEL, LUMINESCENT LAQUER TECHNIQUE.



MACH 4 25, TUNNEL 2, Re ~ 16 x 10^6, ↓ INDICATES TRANSITION POINT

FIG. 6 TYPICAL SCHLIEREN PICTURE OF TRANSITION IN THE BOUNDARY LAYER OF THE STANDARD CONE MODEL

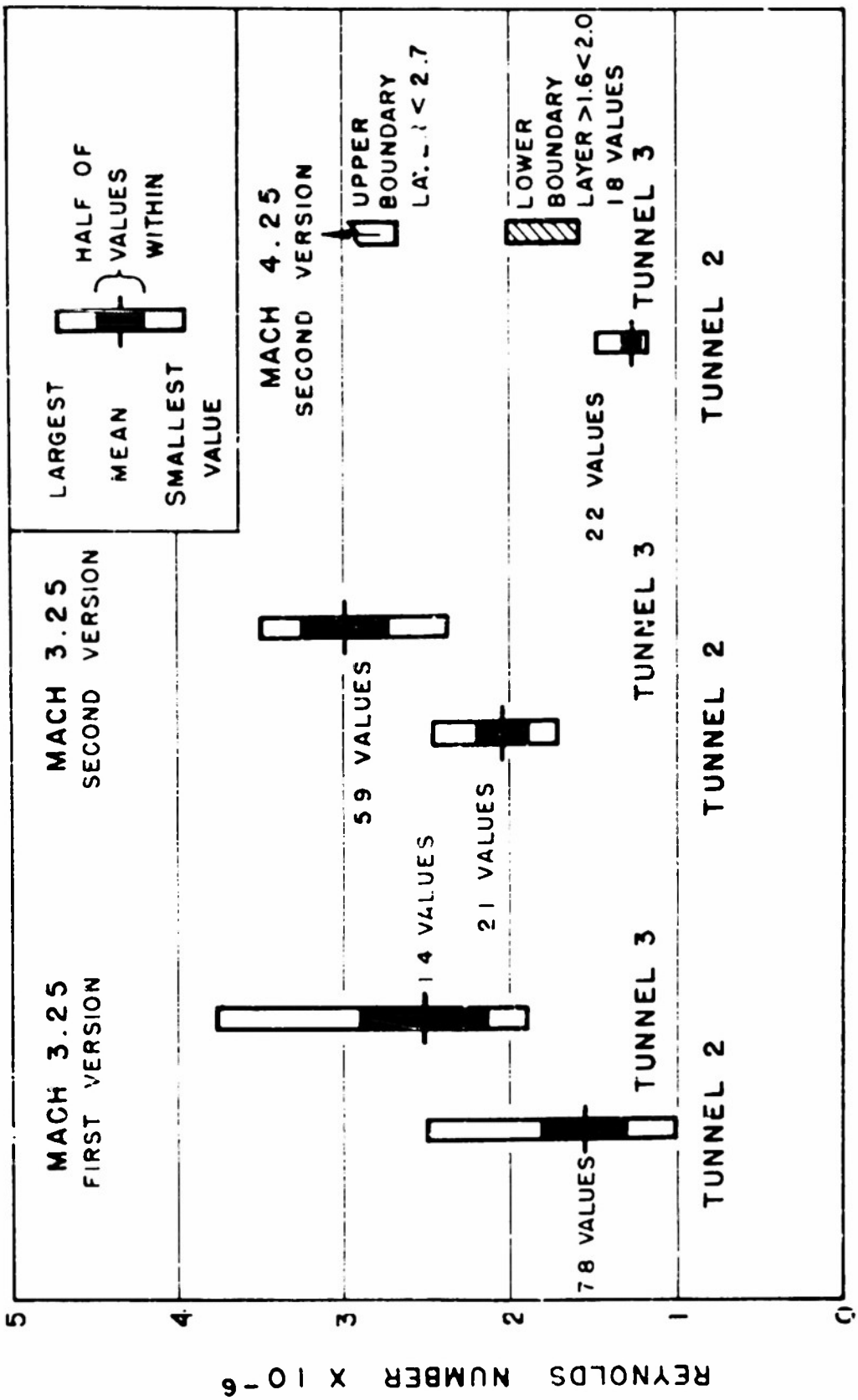


FIG. 7 COMPARISON OF TRANSITION REYNOLDS NUMBER IN TUNNEL 2 AND 3

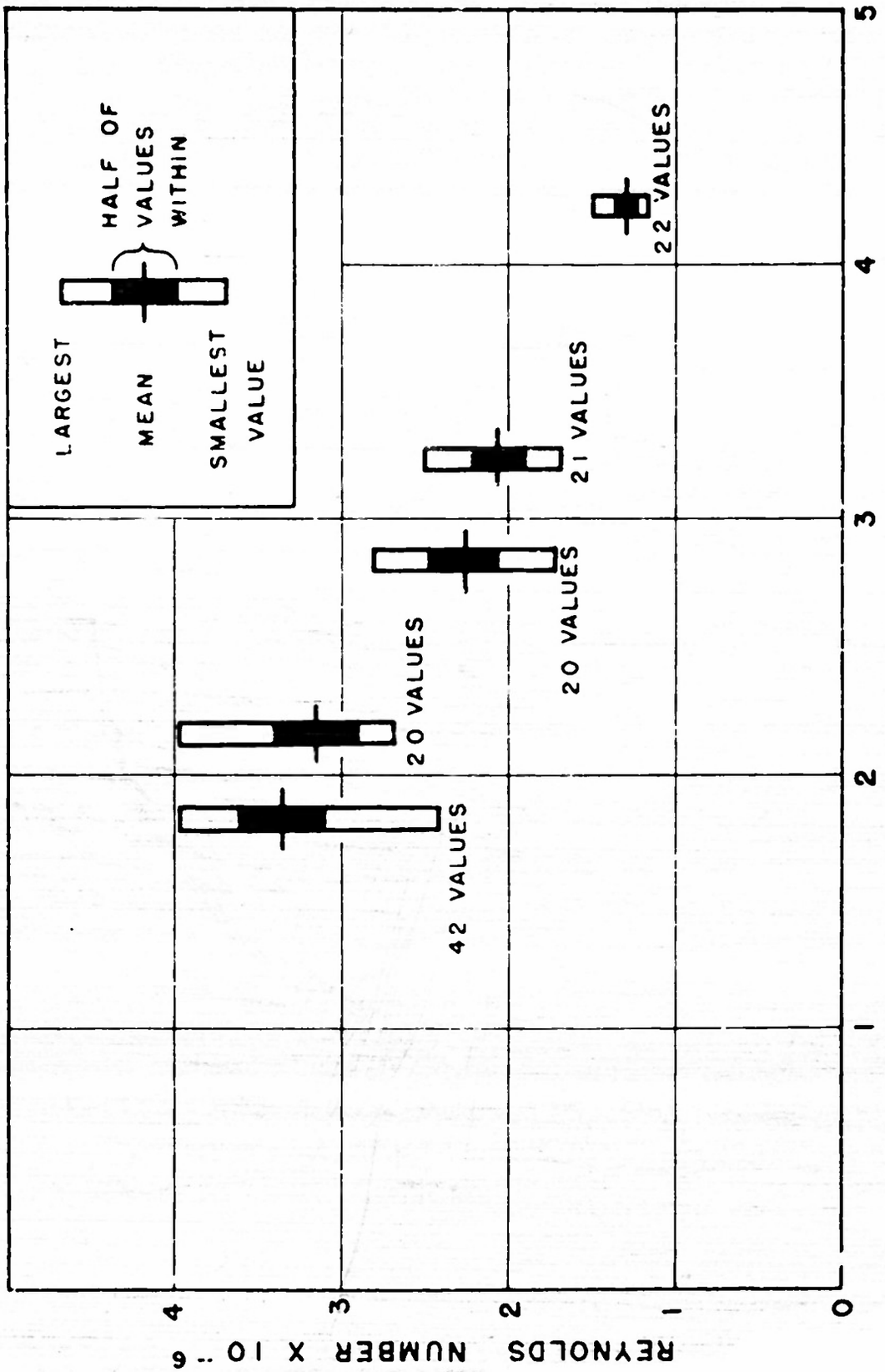


FIG. 8 TRANSITION REYNOLDS NUMBER IN TUNNEL 2 AT VARIOUS MACH NUMBERS

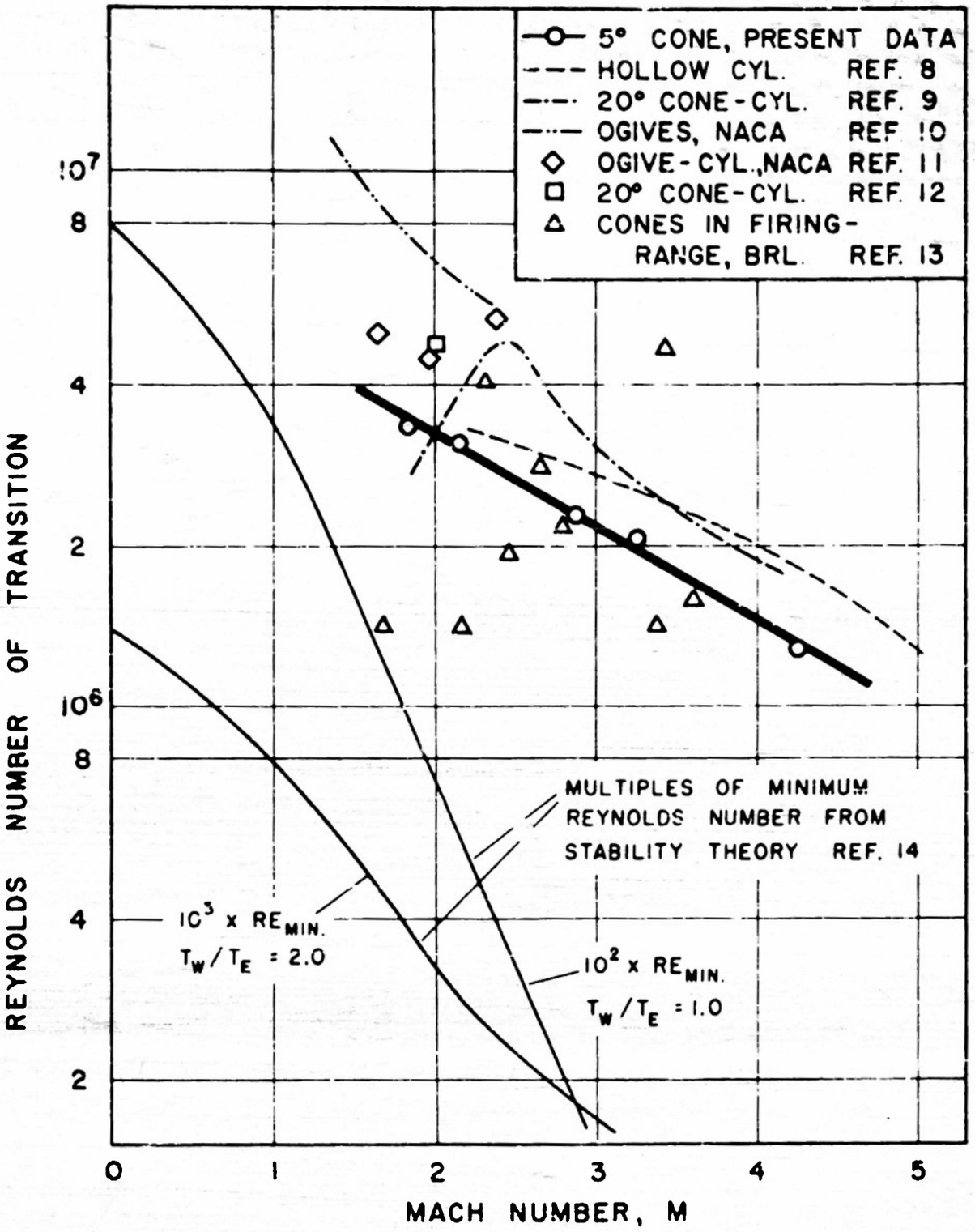


FIG. 9 VARIATION OF REYNOLDS NUMBER OF TRANSITION WITH MACH NUMBER FOR BODIES OF REVOLUTION

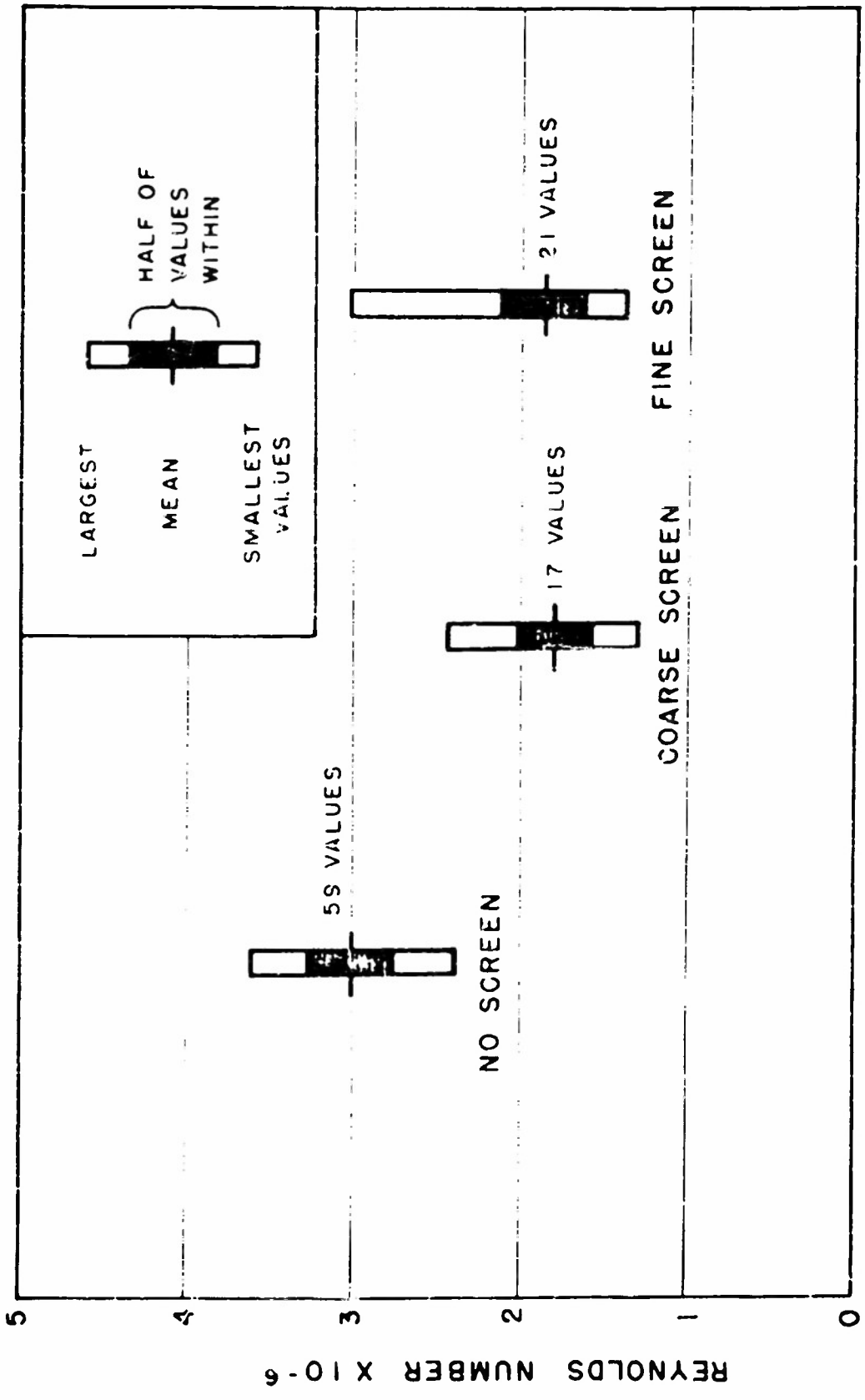


FIG. 10 EFFECT OF SCREENS LOCATED IN SUBSONIC PART OF TUNNEL 3 ON REYNOLDS NUMBER OF TRANSITION, M = 3.25

Aeroballistic Research Department
External Distribution List for Aeroballistics Research (X1a)

No of Copies	
6	Office of Naval Research Branch Office Navy 100 Fleet Post Office New York, New York
	Commanding General Aberdeen Proving Ground Aberdeen, Maryland
1	Attn: Dr B L Hicks
	National Bureau of Standards Aerodynamics Section Washington 25, D C
1	Attn: Dr G B Schubauer, Chief
	Ames Aeronautical Laboratory Moffett Field, California
1	Attn: Walter G Vincenti
	University of California Observatory 21 Berkeley 4, California
1	Attn: Leland E Cunningham VIA: InsMat
	Massachusetts Inst of Technology Dept of Mathematics, Room 2-270 77 Massachusetts Avenue Cambridge, Massachusetts
1	Attn: Prof Eric Reissner VIA: InsMat
	Graduate School Aeronautical Engr Cornell University Ithaca, New York
1	Attn: W R Sears, Director VIA: ONR
	Applied Math and Statistics Lab Stanford University Stanford, California
1	Attn: R J Langle, Associate Dir VIA: Ass't InsMat
	University of Minnesota Dept of Aeronautical Engr Minneapolis, Minnesota
1	Attn: Professor R Hermann VIA: Ass't InsMat
	Case Institute of Technology Dept of Mechanical Engineering Cleveland, Ohio
1	Attn: Professor G Kuerti VIA: ONR
	Harvard University 109 Pierce Hall Cambridge 38, Massachusetts
1	Attn: Professor R von Mises

Aeroballistic Research Department
External Distribution List for Development (X2)

No. of Copies	
	Chief, Bureau of Ordnance Department of the Navy Washington 25, D. C.
1	Attn: Rea
1	Attn: Rexe
1	Attn: Re3d
3	Attn: Re9a
	Chief, Bureau of Aeronautics Department of the Navy Washington 25, D. C
1	Attn: AER-TD-414
2	Attn: RS-7
	Commander U.S. Naval Ordnance Test Station Inyokern P.O. China Lake, California
2	Attn: Technical Library
	Commander U.S. Naval Air Missile Test Center Point Mugu, California
3	Attn: Technical Library
	Superintendent U.S. Naval Postgraduate School Monterey, California
1	Attn: Librarian
	Commanding Officer and Director David Taylor Model Basin Washington 7, D. C.
1	Attn: Hydrodynamics Laboratory
	Chief of Naval Research Navy Research Section Library of Congress
2	Washington 25, D. C.
	Chief, Naval Operations Department of the Navy Washington 25, D. C.
1	Attn: Op-51
	Office of Naval Research Department of the Navy Washington 25, D. C.
2	Attn: Code 463
	Director Naval Research Laboratory Washington 25, D. C.
1	Attn: Code 2021 Code 3800
	Officer-in-Charge Naval Aircraft Torpedo Unit U.S. Naval Air Station
1	Quonset Point, Rhode Island
	Office, Chief of Ordnance Washington 25, D. C.
1	Attn: ORDTU

No. of Copies	
	Research and Development Board Library Branch Pentagon 3D1041
2	Washington 25, D. C.
	Chief, AFSWP P.O. Box 2610 Washington, D. C.
1	Attn: Technical Library
	Chief, Physical Vulnerability Branch Air Targets Division Directorate of Intelligence Headquarters, USAF
1	Washington 25, D. C.
	The Artillery School Antiaircraft and Guided Missiles Br Fort Bliss, Texas
2	Attn: Research and Analysis Sec.
	Commanding General Wright Air Development Center Wright-Patterson Air Force Base Dayton, Ohio
8	Attn: WCAPD
2	Attn: WCRR
1	Attn: WCSD
5	Attn: WCSO
	Director Air University Library
1	Maxwell Air Force Base, Alabama
	Commanding General Aberdeen Proving Ground Aberdeen, Maryland
1	Attn: C. L. Poor
	National Bureau of Standards Washington 25, D. C.
1	Attn: Librarian (Ord. Dev. Div.)
1	Attn: W. Ramberg
	National Bureau of Standards Corona Laboratories (Ord Dev. Div.) Corona, California
1	Attn: Dr. H. Thomas
	National Bureau of Standards Building 3U, UCLA Campus 405 Hilgard Avenue Los Angeles 24, California
1	Attn: Librarian
	University of California Berkeley 4, California
1	Attn: Mr. G. J. Maslach
1	Attn: Dr. S. A. Schaaf
	California Inst. of Technology Pasadena 4, California
2	Attn: Librarian(Guggenheim Aero. Lab.) VIA: BuAero

No. of Copies

University of Michigan
Willow Run Research Center
Ypsilanti, Michigan
1 Attn: L.R Bissell
VIA: InsMat

University of Minnesota
Rosemount, Minnesota
1 Attn: J Leonard Frame
VIA: Ass't InsMat

The Ohio State University
Columbus, Ohio
1 Attn: G.L VonEschen
VIA: Ass't InsMat

Polytechnic Institute of Brooklyn
99 Livingston Street
Brooklyn 2, New York
1 Attn: Dr. Antonio Ferri
VIA: ONR Branch Office

Princeton University
Forrestal Research Center Library
Project Squid
1 Princeton, New Jersey

Massachusetts Inst. of Technology
Project Meteor
Cambridge 39, Massachusetts
2 Attn: Guided Missiles Library

Applied Physics Laboratory
The Johns Hopkins University
8621 Georgia Avenue
Silver Spring, Maryland
1 Attn: Arthur G Norris
Technical Reports Office
VIA: NIO

Armour Research Foundation
35 West 33rd Street
Chicago 16, Illinois
1 Attn: Engr. Mechanics Division
VIA: ONR Branch Office

Defense Research Laboratory
University of Texas
Box 1, University Station
1 Austin, Texas
VIA: InsMat

Eastman Kodak Company
Navy Ordnance Division
50 West Main Street
Rochester 4, New York
2 Attn: Dr. Herbert Trotter, Jr.
VIA: NIO

No. of Copies

General Electric Company
Building #1, Campbell Avenue Plant
Schenectady, New York
1 Attn: J.C. Hoffman
VIA: InsMachinery

The Rand Corporation
1500 Fourth Street
Santa Monica, California
1 Attn: The Librarian
VIA: InsMat

Consolidated Vultee Corporation
Daingerfield, Texas
1 Attn: J.E. Arnold, Manager
VIA: Dev. Contract Office

Douglas Aircraft Company, Inc.
3000 Ocean Park Boulevard
Santa Monica, California
1 Attn: Mr. E.F. Burton
VIA: BuAero Resident Rep.

North American Aviation, Inc.
12214 Lakewood Boulevard
Downey, California
2 Attn: Aerophysics Laboratory
VIA: BuAero Rep.

National Advisory Committee for Aero.
1724 F Street Northwest
Washington 25, D. C.
5 Attn: Mr. E. B Jackson

Ames Aeronautical Laboratory
Moffett Field, California
1 Attn: H Julian Allen
2 Attn: A.C Charters

Theoretical Aerodynamics Division
Langley Aeronautical Laboratory
Langley Field, Virginia
1 Attn: Theoretical Aerodynamics Div
1 Attn: Dr. A Busemann
2 Attn: J. Steele

NACA Lewis Flight Propulsion Lab.
Cleveland Hopkins Airport
Cleveland, Ohio
1 Attn: Dr John C Evvard

Hughes Aircraft Company
Culver City, California
1 Attn: Dr. Allen E Puckett

Institute of Aerophysics
University of Toronto
Toronto 5, Ontario
1 Attn: Dr. Gordon N. Patterson, Dir.
VIA: BuOrd (Ad8)